ELECTROMAGNETIC METAMATERIALS: TRANSMISSION LINE THEORY AND MICROWAVE APPLICATIONS

The Engineering Approach

CHRISTOPHE CALOZ
École Polytechnique de Montréal

TATSUO ITOH
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To Dominique, Maxime, and Raphaël
Christophe

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PREFACE

This book is essentially the fruit of a research work carried out at University of California, Los Angeles (UCLA), from 2002 to 2004 in the context of a Multidisciplinary University Research Initiative (MURI) program. The main participants in this program, in addition to the authors, were John Pendry (Imperial College), David Smith (formerly University of California, San Diego (UCSD), now Duke University), Sheldon Schultz (UCSD), Xiang Zhang (formerly UCLA, now University of California, Berkeley), Gang Chen (formerly UCLA, now Massachusetts Institute of Technology (MIT)), John Joannopoulos (MIT) and Eli Yablonovitch (UCLA).

During these years of infancy for metamaterials (MTMs), which emerged from the first experimental demonstration of a left-handed (LH) structure in 2000, the vast majority of the groups involved in research on MTMs had been focusing on investigating from a physics point of view the fundamental properties of LH media predicted by Veselago in 1967. Not following this trend, the authors adopted an engineering approach, based on a generalized transmission line (TL) theory, with systematic emphasis on developing practical applications, exhibiting unprecedented features in terms of performances or functionalities. This effort resulted in the elaboration of the powerful composite right/left-handed (CRLH) MTM concept, which led to a suite of novel guided-wave, radiated-wave, and refracted-wave devices and structures.

This book presents electromagnetic MTMs and their applications in the general framework of CRLH TL MTMs. Chapter 1 introduces MTMs from a historical perspective and points out their novelty compared with conventional periodic backward-wave media. Chapter 2 exposes the fundamentals of ideal[1]

[1]"Ideal" designates here perfectly homogeneous and isotropic volumic (left-handedness along the three directions of space) materials.

LH MTMs, including the antiparallelism existing between phase/group velocities, the frequency dispersion required from entropy conditions, the modified boundary conditions, the modified Fresnel coefficients, the reversal of classical phenomena [Doppler effect, Vavilov-Čerenkov radiation, Snell's law (negative refractive index, NRI), Goos-Hänchen effect, lenses convergence/divergence], and focusing by a flat "lens" and subwavelength diffraction. Chapter 3 establishes the foundations of CRLH structures, in three progressive steps: ideal TL, LC network, and real distributed structure. Chapter 4 extends theses foundations to the two-dimensional (2D) case, develops a transmission matrix method (TMM) and a transmission line method (TLM) techniques to address the problem of finite-size 2D MTMs excited by arbitrary sources, illustrates by TLM simulations a few NRI effects occurring in 2D MTMs (backward-wave propagation, negative refraction by a RH-LH interface, a LH slab, a LH prism, inner reflection of Gaussian beams in a LH prism, and a LH "perfectly absorbing reflector"), and describes real distributed implementations of 2D MTMs. Chapter 5 presents guided-wave applications of CRLH TL MTMs, including dual-band components, enhanced-bandwidth components, a super-compact multilayer "vertical" structure, tight edge-coupled directional couplers, and negative/zeroth-order resonators. Chapter 6 presents radiated-wave applications of CRLH TL MTMs, including 1D or 2D frequency-scanned and electronically scanned leaky-wave antennas and reflecto-directive systems. Finally, future challenges and prospects of MTMs, including homogenized MTMs, quasi-optical NRI lenses, 3D isotropic LH structures, optical MTMs, magnetless magnetic MTMs, surface plasmonic MTMs, MTMs antenna radomes and frequency selective surfaces, nonlinear, and active MTMs, are discussed in Chapter 7.

It is hoped that the engineering approach of MTMs presented in this book will pave the way for a novel generation of microwave and photonic devices and structures.

C. Caloz and T. Itoh

Montéal, Québec, and Los Angeles, California

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C. C. AND T. I.

ACRONYMS

ATR	Attenuated total reflection
BCs	Boundary conditions
BE	Backfire-to-endfire
BWO	Backward-wave oscillator
BZ	Brillouin zone
CRLH	Composite right/left-handed
CLC	Coupled-line coupler
DB	Dual-band
DPDS	Dual-passband dual-stopband
FDTD	Finite-difference time domain
FEM	Finite-element method
FSS	Frequency selective surface
GVD	Group velocity dispersion
IC	Impedance coupling or coupler
LH	Left-handed
LTCC	Low-temperature cofired ceramics
LW	Leaky-wave
MIM	Metal-insulator-metal
MTM	Metamaterial
MLV	Multilayered vertical
MoM	Method of moments
MRI	Magnetic resonance imaging
MSBVW	Magnetostatic backward volume wave
NRI	Negative refractive index
OPL	Optical path length

PC	Phase coupling or coupler
PCB	Printed circuit board
PBCs	Periodic boundary conditions
PBG	Photonic band-gap
PPWG	Parallel-plate waveguide
PLH	Purely left-handed
PRH	Purely right-handed
QH	Quadrature hybrid
RH	Right-handed
RCS	Radar cross section
RDS	Reflecto-directive system
RRC	Rat-race coupler
SHPM	Subharmonically pumped mixer
SP	Surface plasmon
SPM	Self-phase modulation
SRR	Split-ring resonator
TE	Transverse electric
TEM	Transverse electric-magnetic
TH	Thin-wire
TL	Transmission line
TLM	Transmission line method
TM	Transverse magnetic
TMA	Transfer matrix algorithm
TMM	Transmission matrix method
TWT	Traveling-Wave Tube
UWB	Ultra wideband
ZOR	Zeroth-order resonator

1

INTRODUCTION

Chapter 1 introduces electromagnetic metamaterials (MTMs) and left-handed (LH) MTMs from a general prospect. Section 1.1 defines them. Section 1.2 presents the theoretical speculation by Viktor Veselago on the existence of "substances with simultaneously negative ε and μ" in 1967, which is at the origin of all research on LH MTMs. Section 1.3 describes the first experimental demonstration of left-handedness in 2000 by Smith et al., and Section 1.4 lists a number of further numerical, theoretical, and experimental confirmations of the fundamental properties of LH structures. The difference between "conventional" backward waves, known for many decades, and LH waves, as well as the essential novelty of LH MTMs, are explained in Section 1.5. Section 1.6 discusses the different terminologies used in the literature to designate LH MTMs. Next, Section 1.7 introduces the transmission line (TL) approach of LH MTMs, which has constituted a decisive step toward microwave applications, and Section 1.8 presents, in a concise manner, the generalized composite right/left-handed (CRLH) concept upon which the whole book is based. Finally, Section 1.9 points out the essential difference existing between photonic crystals or photonic band-gap (PBG) structures, more conventionally simply called "periodic structures", and MTMs.

1.1 DEFINITION OF METAMATERIALS (MTMs) AND LEFT-HANDED (LH) MTMs

Electromagnetic metamaterials (MTMs) are broadly defined as *artificial effectively homogeneous electromagnetic structures with unusual properties not readily*

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available in nature. An *effectively homogeneous* structure is a structure whose *structural average cell size* p is *much smaller than the guided wavelength* λ_g. Therefore, this average cell size should be at least smaller than a quarter of wavelength, $p < \lambda_g/4$. We will refer to the condition $p = \lambda_g/4$ as the *effective-homogeneity limit* or *effective-homogeneity condition*[1], to ensure that *refractive phenomena* will dominate over *scattering/diffraction* phenomena when a wave propagates inside the MTM medium. If the condition of effective-homogeneity is satisfied, the structure behaves as a real material in the sense that electromagnetic waves are essentially *myopic to the lattice* and only probe the average, or effective, macroscopic and well-defined *constitutive parameters, which depend on the nature of the unit cell*; the structure is thus *electromagnetically uniform* along the direction of propagation. The constitutive parameters are the permittivity ε and the permeability μ, which are related to the refractive index n by

$$n = \pm\sqrt{\varepsilon_r \mu_r}, \tag{1.1}$$

where ε_r and μ_r are the relative permittivity and permeability related to the free space permittivity and permeability by $\varepsilon_0 = \varepsilon/\varepsilon_r = 8.854 \cdot 10^{-12}$ and $\mu_0 = \mu/\mu_r = 4\pi \cdot 10^{-7}$, respectively. In (1.1), sign $\pm$ for the double-valued square root function has been a priori admitted for generality.

The four possible sign combinations in the pair (ε, μ) are $(+, +)$, $(+, -)$, $(-, +)$, and $(-, -)$, as illustrated in the $\varepsilon - \mu$ diagram of Fig 1.1. Whereas the first three combinations are well known in conventional materials, the last one $[(-, -)]$, with *simultaneously negative permittivity and permeability*, corresponds to the new class of left-handed (LH) materials.[2] LH materials, as a consequence of their double negative parameters, are characterized by antiparallel phase and group velocities, or negative refractive index (NRI) [negative sign in Eq. (1.1)], as will be shown in Chapter 2.

LH structures are clearly MTMs, according to the definition given above, since they are artificial (fabricated by human hands), effectively homogeneous ($p < \lambda_g/4$), and exhibit highly unusual properties ($\varepsilon_r, \mu_r < 0$). It should be noted that, although the term MTM has been used most often in reference to LH structures in the literature, MTMs may encompass a much broader range of

[1] This limit corresponds to a rule of thumb effectiveness condition. Microwave engineers often use the limit $p = \lambda_g/4$, where p is the size of the component considered, to distinguish lumped components ($p < \lambda_g/4$) from quasi-lumped components ($\lambda_g/4 < p < \lambda_g/2$) and distributed components ($p > \lambda_g/2$) [1]. In the lumped case, the phase variation of the signal from the input to the output of the component is negligible, and the component may therefore be considered as a localized (sizeless) element. In contrast, in the distributed case, phase variation along the component cannot be ignored, and the component must consequently be considered as a transmission line section. MTMs are thus "distributed structures constituted of lumped elements."

[2] It should be noted that thin ferrimagnetic films biased in the plane of the film support magnetostatic backward volume wave (MSBVW) in the direction of bias, which may be seen as a LH phenomenon (Section 2.1) in a *real* material. However, this phenomenon is strictly dependent on the thin slab shape of the film and could not exist per se in a bulk ferrite and is therefore not an isotropic LH effect.

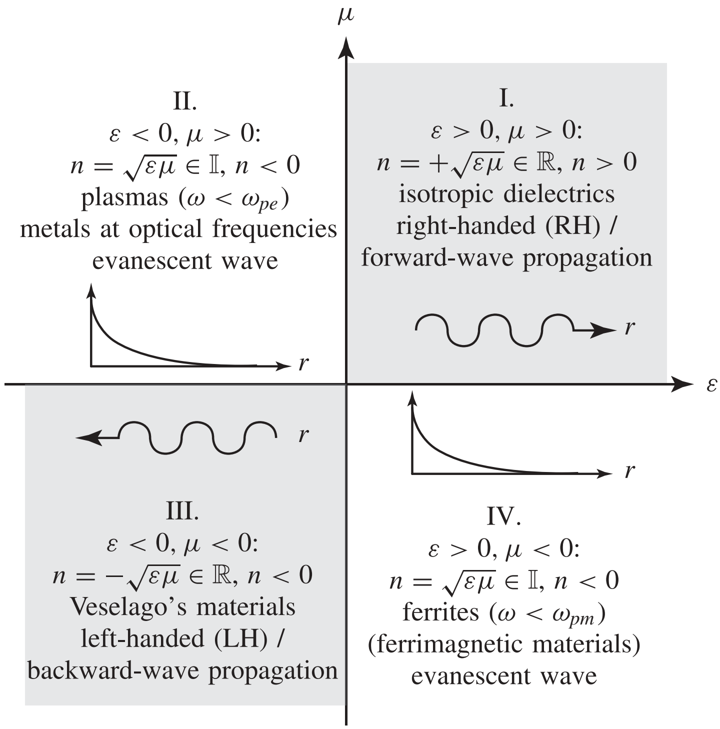


Fig. 1.1. Permittivity-permeability ($\varepsilon - \mu$) and refractive index (n) diagram. The time dependence $e^{+j\omega t}$, associated with the *outgoing* wave function $e^{-j\beta r}$ or *incoming* wave function $e^{+j\beta r}$, where β is the propagation constant, $\beta = nk_0$ ($k_0 = \omega/c$: free space wavenumber, ω: angular frequency, c: speed of light), is assumed. The angular frequencies ω_{pe} and ω_{pm} represent the electric and magnetic plasma frequencies, respectively. $\mathbb{R}$, purely real. $\mathbb{I}$, purely imaginary.

structures.[3] However, LH structures have been by far the most popular of the MTMs, due to their exceptional property of negative refractive index (Chapter 2). This book mainly deals with this class of MTMs and, more precisely, with composite right/left-handed (CRLH) MTMs (Section 1.8), which constitute a generalization of LH MTMs.

1.2 THEORETICAL SPECULATION BY VIKTOR VESELAGO

The history of MTMs started in 1967 with the visionary speculation on the existence of *"substances with simultaneously negative values of* ε *and* μ*"* (fourth

[3]Examples are MTMs with only one of the two constitutive parameters negative, anisotropic MTMs, or any type of functional effective engineered structure. In addition, many existing materials obtained by novel nanotechnology and chemistry processes may be regarded as MTMs.

quadrant in Fig 1.1) by the Russian physicist Viktor Veselago [3].[4] In his paper, Veselago called these "substances" LH to express the fact that they would allow the propagation of electromagnetic waves with the electric field, the magnetic field, and the phase constant vectors building a left-handed triad, compared with conventional materials where this triad is known to be *right-handed* (Section 2.1).

Several fundamental phenomena occurring in or in association with LH media were predicted by Veselago:

1. Necessary frequency dispersion of the constitutive parameters (Section 2.2).
2. Reversal of Doppler effect (Section 2.4).
3. Reversal of Vavilov-Cerenkov radiation (Section 2.5).
4. Reversal of the boundary conditions relating the normal components of the electric and magnetic fields at the interface between a conventional/right-handed (RH) medium and a LH medium (Section 2.3).
5. Reversal of Snell's law (Section 2.6).
6. Subsequent negative refraction at the interface between a RH medium and a LH medium (Section 2.6).
7. Transformation of a point source into a point image by a LH slab (Section 2.6).
8. Interchange of convergence and divergence effects in convex and concave lenses, respectively, when the lens is made LH (Section 2.6).
9. Plasmonic expressions of the constitutive parameters in resonant-type LH media (Section 1.3).

Veselago concluded his paper by discussing potential *real* (natural) "substances" that could exhibit left-handedness. He suggested that "gyrotropic substances possessing plasma and magnetic properties" ("pure ferromagnetic metals or semiconductors"), "in which both ε and μ are tensors" (anisotropic structures), could possibly be LH.[5] However, he recognized, "Unfortunately, . . . , we do not know of even a single substance which could be isotropic and have $\mu < 0$," thereby pointing out how difficult it seemed to realize a practical LH structure. No LH material was indeed discovered at that time.

1.3 EXPERIMENTAL DEMONSTRATION OF LEFT-HANDEDNESS

After Veselago's paper, more than 30 years elapsed until the first LH material was conceived and demonstrated experimentally. This LH material was not a natural substance, as expected by Veselago, but an *artificial* effectively homogeneous

[4]This paper was originally published in Russian in 1967 and then translated into English in 1968. In this translation, the date of 1964 is indicated by mistake as the publication year of the original Russian version.

[5]This is indeed the case, in a restricted sense, of ferrite films supporting MSBVWs, as pointed out in note 2.

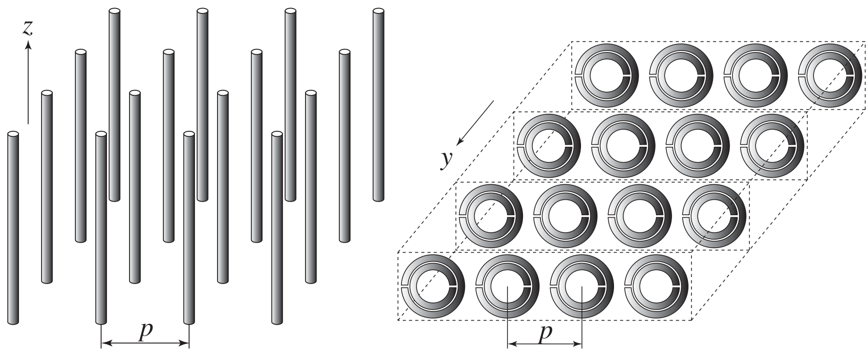


Fig. 1.2. First negative-ε/positive-μ and positive-ε/negative-μ MTM ($p \ll \lambda_g$), constituted only by standard metals and dielectrics, proposed by Pendry. (a) Thin-wire (TW) structure exhibiting negative-ε/positive-μ if $\mathbf{E}\|z$ [6]. (b) Split-ring resonator (SRR) structure exhibiting positive-ε/negative-μ if $\mathbf{H}\perp y$ [7].

structure (i.e., a MTM), which was proposed by Smith and colleagues at University of California, San Diego (UCSD) [4].[6] This structure was inspired by the pioneering works of Pendry at Imperial College, London. Pendry introduced the *plasmonic-type* negative-ε/positive-μ and positive-ε/negative-μ structures shown in Fig 1.2, which can be designed to have their *plasmonic frequency in the microwave range*.[7] Both of these structures have an average cell size p much smaller than the guided wavelength λ_g ($p \ll \lambda_g$) and are therefore effectively homogeneous structures, or MTMs.

The negative-ε/positive-μ MTM is the *metal thin-wire (TW)* structure shown in Fig 1.2(a). If the excitation electric field $\mathbf{E}$ is parallel to the axis of the wires ($\mathbf{E}\|z$), so as to induce a current along them and generate equivalent electric dipole moments,[8] this MTM exhibits a plasmonic-type permittivity frequency function of the form [5, 6]

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + j\omega\zeta} = 1 - \frac{\omega_{pe}^2}{\omega^2 + \zeta^2} + j\frac{\zeta\omega_{pe}^2}{\omega(\omega^2 + \zeta^2)}, \tag{1.2}$$

where $\omega_{pe} = \sqrt{2\pi c^2/[p^2 \ln(p/a)]}$ (c: speed of light, a: radius of the wires) is the *electric plasma frequency*, tunable in the GHz range, and $\zeta = \varepsilon_0(p\omega_{pe}/a)^2/\pi\sigma$

[6]The fact that this first LH MTM was artificial, as all the other LH MTMs known to date!, does not at all exclude that natural substances exhibiting left-handedness could be discovered some day. Because left-handedness is allowed by fundamental physics laws in artificial structures, there is no reason why it would not be also possible in natural substances.

[7]This is distinct from conventional gas and metal plasmas, which have their plasma frequency far above the microwave range, preventing negative ε at microwave frequencies.

[8]If the electric field $\mathbf{E}$ is perfectly parallel to the axis of the wires (z), a maximum of effect is obtained. If it is exactly perpendicular to the wires, we have a situation of cross polarization, where no effect is produced. In the intermediate situation where the electric field is oblique with respect to the wires, a reduced effect occurs, decreasing as the angle with the wires increases.

(σ: conductivity of the metal) is a damping factor due to metal losses. It clearly appears in this formula that

$$\mathrm{Re}(\varepsilon_r) < 0, \quad \text{for} \quad \omega^2 < \omega_{pe}^2 - \zeta^2, \tag{1.3a}$$

which reduces if $\zeta = 0$ to

$$\varepsilon_r < 0, \quad \text{for} \quad \omega < \omega_{pe}. \tag{1.3b}$$

On the other hand, permeability is simply $\mu = \mu_0$, since no magnetic material is present and no magnetic dipole moment is generated. It should be noted that the wires are assumed to be much longer than wavelength (theoretically infinite), which means that the wires are excited at frequencies situated far below their first resonance.

The positive-ε/negative-μ MTM is the *metal split-ring resonator (SRR)* structure[9] shown in Fig 1.2(b). If the excitation magnetic field $\mathbf{H}$ is perpendicular to the plane of the rings ($\mathbf{H}\perp y$), so as to induce resonating currents in the loop and generate equivalent *magnetic dipole moments*,[10] this MTM exhibits a plasmonic-type permeability frequency function of the form [7]

$$\begin{aligned}\mu_r(\omega) &= 1 - \frac{F\omega^2}{\omega^2 - \omega_{0m}^2 + j\omega\zeta} \\ &= 1 - \frac{F\omega^2(\omega^2 - \omega_{0m}^2)}{(\omega^2 - \omega_{0m}^2)^2 + (\omega\zeta)^2} + j\frac{F\omega^2\zeta}{(\omega^2 - \omega_{0m}^2)^2 + (\omega\zeta)^2},\end{aligned} \tag{1.4}$$

where $F = \pi(a/p)^2$ (a: inner radius of the smaller ring), $\omega_{0m} = c\sqrt{\frac{3p}{\pi \ln(2wa^3/\delta)}}$ (w: width of the rings, δ: radial spacing between the rings) is a magnetic resonance frequency, tunable in the GHz range, and $\zeta = 2pR'/a\mu_0$ (R': metal resistance per unit length) is the damping factor due to metal losses. It should be noted that the SRR structure has a magnetic response despite the fact that it does not include magnetic conducting materials due to the presence of artificial magnetic dipole moments provided by the ring resonators. Eq. (1.4) reveals that a frequency range can exist in which $\mathrm{Re}(\mu_r) < 0$ in general ($\zeta \neq 0$). In the loss-less case ($\zeta \neq 0$), it appears that

$$\mu_r < 0, \quad \text{for} \quad \omega_{0m} < \omega < \frac{\omega_{0m}}{\sqrt{1-F}} = \omega_{pm}, \tag{1.5}$$

where ω_{pm} is called the *magnetic plasma frequency*. An essential difference between the plasmonic expressions of ε and μ is that the latter is of *resonant*

[9]One single ring in the unit cell produces qualitatively identical effects, but the magnetic activity, effective permeability and bandwidth, is enhanced by the presence of a second ring due to larger overall current and slightly different overlapping resonances.

[10]A remark analogous to that of note 8 holds here under the substitutions $\mathbf{E} \to \mathbf{H}$ and $z \to y$.

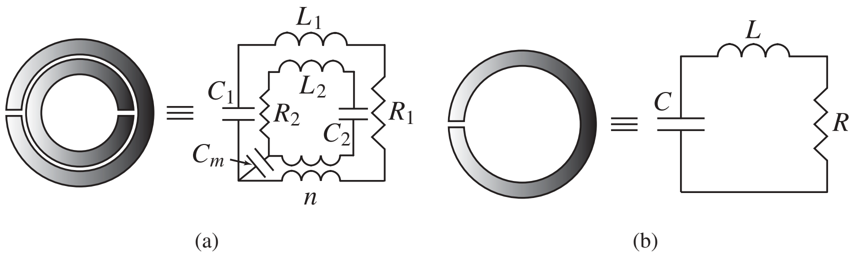


Fig. 1.3. Equivalent circuit model of SRRs. (a) Double SRR configuration (e.g., [7]). (b) Single SRR configuration.

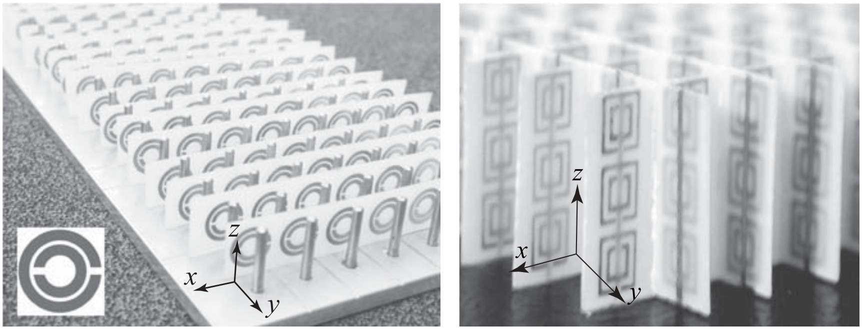
nature $[\mu(\omega = \omega_{0m}) = \infty]$, whereas the former is a nonresonant expression. The resonance of the structure is due to the resonance of its SRRs, given in [7] by $\omega_{0m}^2 = 3pc^2/[\pi \ln(2w/\delta]a^3)$ (p: period, $c = 1/\sqrt{\varepsilon_0\mu_0}$: speed of light, w: width of the rings, δ: spacing between the rings).

The equivalent circuit of a SRR is shown in Fig 1.3 [8]. In the double ring configuration [Fig 1.3(a)], capacitive coupling and inductive coupling between the larger and smaller rings are modeled by a coupling capacitance (C_m) and by a transformer (transforming ratio n), respectively. In the single ring configuration [Fig 1.3(b)], the circuit model is that of the simplest RLC resonator with resonant frequency $\omega_0 = 1/\sqrt{LC}$. The double SRR is essentially equivalent to the single SRR if mutual coupling is weak, because the dimensions of the two rings are very close to each other, so that $L_1 \approx L_2 \approx L$ and $C_1 \approx C_2 \approx C$, resulting in a combined resonance frequency close to that of the single SRR with same dimensions but with a larger magnetic moment due to higher current density.

In [4], Smith et al. combined the TW and SRR structures of Pendry into the composite structure shown in Fig 1.4(a), which represented the first experimental LH MTM prototype. The arguments in [4] consisted of the following: 1) designing a TW structure and a SRR structure with overlapping frequency ranges of negative permittivity and permeability; 2) combining the two structures into a composite TW-SRR structure, which is shown in Fig 1.4(a); and 3) launching an electromagnetic wave $e^{-j\beta r}$ through the structure and concluding from a fact that a passband (or maximum transmission coefficient, experimentally) appears in the frequency range of interest proves that the constitutive parameters are simultaneously negative in this range on the basis of the fact that $\beta = nk_0 = \pm\sqrt{\varepsilon_r\mu_r}$ has to be real in a passband.

Although the arguments of [4] were questionable, because it ignored the fact that coupling interactions between the two constituent structures could yield properties totally different from the superposition of the properties of each structure taken separately,[11] a vivid experimental demonstration of the LH nature of the TW-SRR was provided in [10]. In this paper, the TW-SRR structure of Fig 1.4(b)

[11]In fact, this structure was really "working" only due to the judicious position of the wires in the symmetry center of the rings, which canceled interactions between the two structures due to induced



(a) (b)

Fig. 1.4. First experimental LH structures, constituted of TWs and SRRs, introduced by the team of UCSD. (a) Monodimensionally LH structure of [4]. (b) Bidimensionally LH structure of [10].

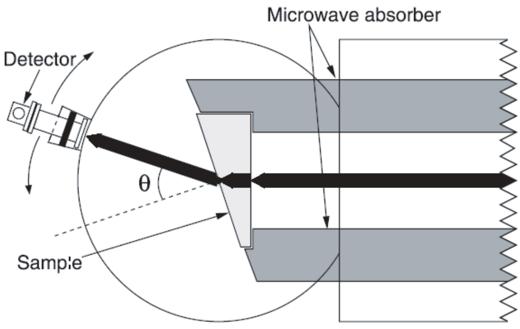


Fig. 1.5. Experimental setup used in [10] for the demonstration of left-handedness of the TW-SRR structure of Fig 1.4(b) at around 5 GHz. "The sample and the microwave absorber were placed between top and bottom parallel, circular aluminum plates spaced 1.2 cm apart. The radius of the circular plates was 15 cm. The black arrows represent the microwave beam as would be refracted by a positive index sample. The detector was rotated around the circumference of the circle in 1.5° steps, and the transmitted power spectrum was measured as a function of angle, θ, from the interface normal. The detector was a waveguide to coaxial adapter attached to a standard X-band waveguide, whose opening was 2.3 cm in the plane of the circular plates. θ as shown is positive in this figure." From [10], © Science; reprinted with permission.

was cut into a wedge-shaped piece of MTM and inserted into the experimental apparatus depicted in Fig 1.5. Left-handedness of the TW-SRR structure was evidenced by the fact that a maximum of the transmission coefficient was measured in the negative angle (below the normal in the figure) with respect to the

currents with opposite signs in the SRRs and TWs [9]. Note that there an other possible symmetry location for the TWs is in the midplanes between the SRRs.

interface of the wedge, whereas a maximum in the positive angle (above the normal) was measured, as expected, when the wedge was replaced by a regular piece of teflon with identical shape. The result reported was in qualitative and quantitative agreement with *Snell's law*, which reads

$$k_1 \sin\theta_1 = k_2 \sin\theta_2, \tag{1.6a}$$

or, if the two media are isotropic (so that $k_1 = n_1 k_0$ and $k_2 = n_2 k_0$),

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{1.6b}$$

where k_i, n_i, and θ_i represent the wavenumber, refractive index, and angle of the ray from the normal to the interface, respectively, in each of the two media considered ($i = 1, \ldots, 2$).

The MTMs described here are *anisotropic*[12] and characterized by uniaxial permittivity and permeability tensors

$$[\varepsilon] = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}, \tag{1.7a}$$

$$[\mu] = \begin{bmatrix} \mu_{xx} & 0 & 0 \\ 0 & \mu_{yy} & 0 \\ 0 & 0 & \mu_{zz} \end{bmatrix}. \tag{1.7b}$$

The structure shown in Fig 1.4(a) is monodimensionally LH, since only one direction is allowed for the doublet (**E**, **H**); we have $\varepsilon_{xx}(\omega < \omega_{pe}) < 0$ and $\varepsilon_{yy} = \varepsilon_{zz} > 0$, $\mu_{xx}(\omega_{0m} < \omega < \omega_{pm}) < 0$ and $\mu_{yy} = \mu_{zz} > 0$. The structure shown in Fig 1.4(b) is bidimensionally LH because, although **E** has to be directed along the axis of the wires, two directions are possible for **H**; then $[\varepsilon]$ is unchanged, but $\mu_{xx}, \mu_{yy} < 0$ for $\omega_{0m} < \omega < \omega_{pm}$ and $\mu_{zz} > 0$.

1.4 FURTHER NUMERICAL AND EXPERIMENTAL CONFIRMATIONS

In the few years after the first experimental demonstration of a LH structure by Smith et al., a large number of both theoretical and experimental reports confirmed the existence and main properties of LH materials predicted by Veselago.[13]

Characterization of the *TW-SRR LH structures* in terms of constitutive parameter functions similar to Eqs. (1.2) and (1.4) was provided by Smith et al. in [12], [13], and [14] and was then abundantly rediscussed and refined by various

[12]It is worth noting that various spatial filtering effects may be obtained from this anisotropic MTM [11].

[13]In 2002, some controversies temporarily cast doubt on these novel concepts [15, 16, 17]. However, these controversies were quickly shown to be based on physics misconceptions (e.g., [35]).

TABLE 1.1. Verification of Main Properties and Fundamental Physics of LH MTMs by Different Approaches and Different Groups.

Type of Investigation	References
Numerical FDTD	Ziolkowski et al. [27, 28]
Numerical FEM	Caloz et al. [29]
Numerical TMA	Markŏs et al. [20, 21]
Numerical TLM	So and Hoefer [30, 31]
Theoretical EM	Lindell et al. [32], Kong et al. [33, 34], Smith et al. [35], McCall et al. [36]
Experimental (bulk) TW-SRR	Shelby et al. [10], Greegor et al. [22], Ziolkowski [26], Marqués et al. [25]
Theoretical TL	Eleftheriades et al. [37, 38], Caloz and Itoh [39, 40], Oliner [41, 42]
Experimental (planar) TL	Iyer et al. [43], Caloz and Itoh [40], Sanada et al. [44]

groups, all confirming the LH nature of these structures (e.g., [18, 19, 20, 21, 22, 23, 24, 25, 26]).

Table 1.1 presents a list of key reports verifying, by different approaches, the main properties and fundamental physics of LH MTMs. The main *numerical methods* used are finite-difference time-domain (FDTD), finite-elements method (FEM), transfer matrix algorithm (TAM), and transmission line method (TLM). The *theoretical* verifications are subdivided into fundamental electromagnetic (EM) theory and transmission line (TL) theory approaches. *Experimental* demonstrations are provided both in TW-SRR bulk structures and planar TL-type structures.

1.5 "CONVENTIONAL" BACKWARD WAVES AND NOVELTY OF LH MTMs

Propagation of waves with antiparallel phase and group velocity is not a new phenomenon. It has been known for many years in the physics and microwave communities in various contexts. Back in the late 1940s, Brillouin and Pierce utilized the series-capacitance/shunt-inductance equivalent circuit model shown in Fig 1.6, which constitutes the starting point of the CRLH TL theory and applications presented in this book, to describe such antiparallel phase/group velocities propagation, and used the term *backward waves* to designate the corresponding waves [45, 46].[14] For Brillouin, backward waves referred to negative space

[14]We may also add Malyuzhinets, who also used the same LC model, after Brillouin and Pierce, in the description of the radiation condition in backward-wave media [47].